

**THE ROLE OF RENEWABLE LIQUID TRANSPORTATION FUELS  
IN CANADA'S CLIMATE ACTION PLAN:**

**Pros and Cons, and Stages of Development of  
Ethanol, Biodiesel and Thermal Depolymerization Oil.**

**A Discussion Paper for the Saskatchewan Environmental Society and the Climate Action  
Network**

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## 1. INTRODUCTION

A number of liquid renewable fuels for application in transportation are in various stages of research, development and commercial application in Canada and elsewhere. Canada's Action Plan calls for use of both ethanol and biodiesel as fuel substitutes to help achieve the Kyoto GHG emission reduction targets.

Ethanol made from grain is being added to gasoline (at the 5-10% level) in various provinces in Canada, with the main production and use in Ontario. Current ethanol production in Canada is slightly above 200 million litres per year. For comparison, gasoline consumption in Canada in the year 2000 was 38 billion litres. Ethanol is produced in the billions of litres in the USA (6.4 billion litres in 2001) and is used as an additive to gasoline for the purposes of reducing air pollution in cities, decreasing US dependence on imported oil and encouraging rural development. Recent studies indicate that ethanol produced from corn grain (the main raw material used in the USA) decreases greenhouse gas emissions compared to gasoline. Thus reduction in greenhouse gas emissions has become a further reason for ethanol production. Ethanol is still more expensive than gasoline in the USA and Canada, so federal, state or provincial subsidies (reduction in taxes) are required to make the ethanol industry viable.

Biodiesel is made by the transesterification of vegetable oils or animal fats and greases with methanol or ethanol. In this process, the large oil or fat triglyceride molecules are reacted with alcohols (usually methanol) in the presence of a catalyst to produce the alcohol esters. These methyl or ethyl esters of fatty acids are called biodiesel. Biodiesel is much less viscous than the original oil or fat and makes a better fuel for diesel engines than do the oils or fats themselves. Glycerol is produced as a byproduct. The main production of biodiesel is in western Europe, where over 1.3 million tonnes (about 1.4 billion litres) is produced annually. Biodiesel is added to diesel fuel to reduce air pollution. Biodiesel is more expensive than diesel fuel and government subsidies are required to encourage its use as a diesel fuel additive. Biodiesel is just starting to be used in Canada, with demonstration trials in Montreal and Saskatoon. Small amounts of canola biodiesel are being sold commercially as a lubricity improvement agent for diesel fuel, based on production by Milligan Biotechnology at Foam Lake, Saskatchewan.

Although there have been various attempts to use vegetable oils directly as diesel fuel, most experts advise against this, citing a number of cases where engines were ruined by using vegetable oils as replacement for diesel fuel (Pratt, 2003). This is in strong contrast to the use of biodiesel, where there is extensive data on the successful use of this product to fuel diesel engines, usually in blends with conventional diesel fuel.

Thermal depolymerization has been found capable of producing an oil from many biomass raw materials, which can be further processed for use as a liquid fuel. The initial oil produced is similar to a mix of fuel oil and gasoline. A company in the USA called Changing World Technologies has developed the process, and the first commercial plant is being built to convert waste from a large turkey processing plant in Carthage, Missouri. The process involves grinding the organic waste, reacting with steam under pressure, flashing off the water, and reacting the initial product from these initial steps under high temperature conditions to produce oil, gas

(used to run the process), carbon (charcoal) and minerals (to be used as fertilizer). The company estimates that it can produce the product oil for about US\$8-12/barrel. The company further estimates that there are enough organic materials, including crop residues, in the USA, to produce about 4 billion barrels of this biomass oil per year, roughly similar to the 4.2 billion barrels of crude fossil-fuel oil imported into the USA every year.

Each of these three renewable liquid fuels will be discussed in the following sections of this overview.

## **2. ETHANOL**

### **2.1. Introduction.**

Canada's climate action plan suggests a 2010 target of 35% of gasoline being sold as a 10% blend of ethanol in gasoline, with an estimated GHG reduction of 0.9 mt (million tonnes) of eCO<sub>2</sub> (carbon dioxide equivalents).

Ethanol is one of the more controversial renewable fuels in commercial use and development. Almost all fuel ethanol produced in North America is made from grain (principally corn grain in the USA and Ontario). There are plans to expand the industry in Canada. The federal government and several provincial governments are actively encouraging the development of the ethanol industry, from the standpoints of both reducing greenhouse gas emissions and encouraging rural development.

The federal government has funded several studies to calculate the energy and greenhouse gas budgets of ethanol made from corn grain in Ontario (Levelton et al., 1999), ethanol made from lignocellulosic raw materials such as grass hays and cereal crop residues (Levelton and (S&T)<sup>2</sup>, 2000) and ethanol made from spring wheat in western Canada ((S&T)<sup>2</sup> Consultants, 2003). All three studies concluded that ethanol has a positive net energy budget, i.e., more renewable energy is produced than fossil fuel is consumed in the whole production and use cycle. Similarly, all three studies found that ethanol produced from these three different raw materials would reduce greenhouse gas emissions considerably, compared to conventional gasoline. Ethanol can also be produced from fast growing trees such as hybrid poplar and willow, and a number of studies have examined the economics and greenhouse gas effects of producing ethanol from such sources (Wang, 1998).

Ethanol made from grains has critics who have questioned the energy budgets, greenhouse gas reduction budgets and economics. In the USA, David Pimentel, College of Agriculture and Life Sciences, Cornell University, Ithaca, NY, has been one of the best known critics. He has questioned the ethics of using a food and feed grain (corn) to produce a fuel for cars and trucks, when so many people are malnourished in the world (Pimentel, 2001). He has claimed that ethanol produced from corn grain in the USA does not have a positive net energy benefit, and that more fossil fuel is used to produce ethanol than is gained as renewable ethanol fuel. Professor Carroll Goering in the USA has also conducted studies of the energy costs of corn production and ethanol production (Goering, 2001). He and his students recently calculated that ethanol made from corn grain returned 1.7 units of renewable energy for every unit of fossil fuel

invested. Pimentel calculated that only 0.59 units of renewable energy were produced for every unit of fossil fuel invested. In Goering's critique of Pimentel's method, he concluded that some of Pimentel's data were out of date and energy credits were not given for co-products produced. However, Goering's analysis did not include the energy costs of the machinery construction and repair, as did Pimentel's analysis.

A recent detailed study of the energy costs of producing ethanol from corn grain in the USA was conducted by the United States Department of Agriculture and the Argonne National Laboratory (Shapouri et al., 2002). This study calculated that corn ethanol was modestly energy efficient as indicated by an energy output:input ratio of 1.34. This analysis did not include the energy costs of machinery production and repair, although Shapouri et al. believed that this would not be a large energy factor.

Pimentel has also questioned expansion of use of lignocellulosic raw materials (such as fast growing trees) for energy, given the expected further increase in demands for food, feed and conventional uses of fiber as world populations continue to rise (Pimentel, 2001). He has stated that the US ethanol industry would not exist without government subsidies, since it is considerably more expensive than gasoline.

Peter Holle, president of the Frontier Centre for Public Policy in Winnipeg, has serious questions about ethanol from grain, at least for the Manitoba situation (Holle, 2002). Some of his concerns are listed as follows:

1. Expansion of ethanol production from grain in Manitoba might depress the livestock industry in Manitoba by raising feed grain prices.
2. The expansion in the hog and cattle business in Manitoba has resulted in such a large demand for feed grain that Manitoba is already a net importer of feed grain.
3. Mandating a 10% blend of ethanol in gasoline in Manitoba would cost Manitoba taxpayers \$35 million per year.
4. Each job created in the ethanol industry in Minnesota costs \$75,000 in subsidies.
5. Energy net gain from making ethanol from grain is relatively small. Small ethanol plants may not be able to achieve a positive energy balance.
6. Burning 10% ethanol blends reduces carbon monoxide and carbon dioxide emissions, but raises emissions of nitrous oxide and hence ozone, and also increases aldehyde emissions. Thus any benefits in terms of reducing air pollutants are small.

REAP-Canada questioned whether grain ethanol was 'green' ethanol, both from the economic and environmental standpoints (Sustainable Farming, 1993). REAP argued that a greater environmental impact could be achieved at lower cost by continuing to raise the price of gasoline, perhaps using "feebates" (taxing gas guzzlers and subsidizing fuel-efficient cars), and establishing toll highways to reduce automobile use while producing revenue with which to subsidize public transportation systems.

The report *Kyoto and Beyond* (Torrie et al., 2002) calculated that greenhouse gas emissions from the personal transportation sector of the Canadian economy could be reduced from 119 million tonnes of eCO<sub>2</sub> (carbon dioxide equivalents) in 2004 to 73 million tonnes of eCO<sub>2</sub> in 2012. This reduction would be achieved by a combination of improvements in the energy

efficiency of vehicles and the employment of 1.3 billion litres of ethanol used in 10% ethanol blends with gasoline. The main reduction in GHG emissions was attributed to improvements in energy efficiency. The federal government plan, according to Torrie (Torrie, 2002) assumed less than one billion litres of ethanol would be produced in 2012. For comparison, gasoline consumption in Canada in the year 2000 was about 38 billion litres (Statistics Canada, 2000).

The purpose of this section is to give an overview of present and future directions in ethanol research and commercial development, and give examples of answers to the questions raised by the critics. This paper should not be considered a definitive review of ethanol pros and cons, but may provide background information about some of the issues.

## **2.2. Different uses for biomass.**

### **2.2.1. Competing uses for biomass.**

Biomass is different from other renewable energy sources, such as wind or direct solar conversion, e.g., photovoltaic generation of electricity, in that there are many competing uses for biomass materials. These different uses include:

- Food,
- Feed for animals,
- Soil protection and soil fertility maintenance (crop residues, roots of crops),
- Fiber products (such as linen (from flax), lumber and pulp and paper),
- Feedstocks for industrial applications (e.g., linseed oil from flax for paints),
- Fuels such as wood for heating, ethanol, biodiesel.

The economic value of these different uses roughly follows the order shown, with fuel products the lowest value in the series. Since fuels from biomass compete with cheap fossil fuels, a strategy to try and improve the economics of production of (for example) ethanol is to produce higher value products, such as food, as coproducts. This should help to improve the economics of the process and reduce the economic cost of the ethanol.

### **2.2.2. Cascading biomass uses: waste products from a high value use can be employed as starting materials for a lower value application.**

The second principle is to consider cascading biomass uses from the highest value to the lowest. Thus a biomass material would first be used for a higher value use. The waste products from this application, or the actual product at the end of its useful lifetime, might be used for a lower value use, such as fuel. For example, the pulp and paper industry chemically treats wood to produce paper pulp. The waste product from this process, called black liquor, is burned to generate process steam and recover the pulping chemicals for reuse. New processes are being developed which could convert the black liquor into alcohols and still recover the pulping chemicals for recycling. The new process, according to the Swedish group studying the process, could significantly increase the profitability of the pulp mill, and also produce large amounts of alcohols. More waste biomass would be brought into the plant to meet the original process energy needs of the mill and the new alcohol production energy requirements.

### **2.3. Methods to produce ethanol.**

The different routes to alcohols will be briefly reviewed to look at their advantages and disadvantages, and their present state of development.

Ethanol is a renewable fuel that can be produced from a variety of biomass resources. There are three main routes to produce ethanol:

#### 2.3.1. Fermentation of starch in grains and fermentation of simple sugars from sugar cane or sugar beet.

Ethanol can be produced by fermentation of starch in raw materials such as corn grain (USA and Ontario) and by fermentation of sugars (sugar cane in Brazil). Most commercial fuel ethanol in the world is produced by fermentation of these two resources. Fermentation of grains also produces a product containing much of the protein and fiber contained in the original grain. This product is called “dried distillers grains and solubles” (DDGS), and it is used as an animal feed. It is produced in roughly the same amount as the ethanol. It is also possible to produce various human grade foods (such as wheat gluten) from cereal grains at the same time as the starch (or a portion of the starch) is converted into ethanol.

#### 2.3.2. Fermentation of sugars produced from lignocellulosic raw materials.

Research and development is ongoing in a number of countries to produce ethanol from lignocellulosic materials such as crop residues (straw, chaff, corn stover), hays (switchgrass) and waste wood. Lignocellulosic raw materials are much more difficult to ferment than starch or sugar sources. Complex chemical and biological processes are needed to break down the cellulose and hemicellulose main constituents of lignocellulosic raw materials into simple sugars and then convert them into ethanol. Current estimates of prices indicate that, at the present state of development, ethanol produced from these lignocellulosic raw materials is still more expensive than ethanol produced from corn grain, which in turn is more expensive than gasoline. The complex processes involved result in high capital costs, which in turn implies that very large plants are needed to generate a profit. Raw material demands per plant could be 300,000 tonnes or more per year.

One of the appeals of producing ethanol from lignocellulosic raw materials is that they are more abundant than grains and lower in price. Furthermore, only limited amounts of ethanol could be produced from grains before there would be competition with grain uses for human food or animal feed. Lignocellulosic raw materials have their limitations of supply as well. For example, a certain proportion of crop residues needs to be left on the field to protect the field from soil erosion and to add fiber and nutrients to the soil. Crop residues are also used as animal feed, and the amounts available for ethanol production are the surplus available after soil protection and animal feed needs are met.

Energy and GHG gas emissions from ethanol produced by this route are discussed in section 2.4.2.



One of the main companies involved in research and development of ethanol from lignocellulose is Iogen, a Canadian company headquartered in the Ottawa area. The Iogen process is sufficiently promising that PetroCanada and Shell have invested significantly in Iogen.

### 2.3.3. Gasification routes to ethanol and other renewable fuels.

A third route to ethanol, or other renewable liquid and gaseous fuels, involves gasification of lignocellulosic materials to produce a mixture of hydrogen and carbon monoxide called synthesis gas. Partial combustion using oxygen or high temperature and pressure steam can be used to gasify raw materials. Different metallic catalysts are then used to convert the synthesis gas into ethanol, methanol, dimethyl ether (a potential renewable diesel fuel substitute) or hydrogen. Experts in gasification technology believe that the gasification route can produce ethanol at a lower price than fermentation routes (e.g., Klass, 1998). In addition, gasification methods can utilize raw materials such as bark and black liquor (a byproduct of kraft pulping of wood), materials which are not possible to ferment to ethanol.

Swedish studies (Lindblom and Berglin, 2001; Berglin et al., 2002) calculated that up to 3.6 million tonnes (4.5 billion L) of methanol could be produced by gasification of black liquor solids produced by Swedish pulp mills. This would replace about 25% of all Swedish transportation fuel needs. Synthesis gas can also be used to produce ethanol, by changing the catalyst used for methanol synthesis (Pearson, 2001; Klass, 1998).

How much ethanol could be produced from the 19 to 24 million tonnes of black liquor solids produced in Canada (Jaques, 1992; Statistics Canada, 2000)? I estimated that the theoretical production of ethanol could be as high as 5.8 to 7.3 billion litres per year, assuming that ethanol weight yields were some 72 % of the methanol yields obtained by Lindblom and Berglin (2001) in the Swedish studies. Because methanol has a lower energy value per litre than ethanol, just about as much fuel energy could be produced from ethanol as from methanol per tonne of black liquor solids gasified. Conversion of black liquor to alcohols would compete with production of steam and electricity at pulp mills, unless considerably more forest residues were collected and brought to the pulp mill, according to the Swedish studies.

## **2.4. Energy and greenhouse gas budgets for producing ethanol.**

### **2.4.1. Ethanol produced from grains.**

Most ethanol produced in the USA and Ontario in Canada is produced from corn grain by a fermentation process that converts the starch in the corn grain to ethanol plus carbon dioxide. About 30% of the original weight of the grain is not converted into ethanol or carbon dioxide and is left as a product enriched in protein and fiber. This product is usually dried to produce an animal feed called dried distillers grains and solubles (DDGS).

The carbon dioxide released by the fermentation process and the carbon dioxide released by burning the ethanol in an engine does not increase the net level of carbon dioxide in the atmosphere. The grain plant converted carbon dioxide in the current atmosphere into grain. Fermentation of the grain and burning of the ethanol simply released this carbon dioxide back

into the atmosphere, completing the cycling of carbon from atmosphere to plants and back again. In contrast, burning fossil fuels releases carbon dioxide which had been sequestered as crude oil out of the atmosphere for millions of years. This leads to a net increase in atmospheric carbon dioxide. Since fossil fuels are used to produce the grain and convert it into ethanol, it is important that this use of fossil fuel be minimized so as to increase the net renewable energy benefit to be obtained from production of this renewable fuel. I.e.: solar energy to grow the grain - fossil fuel energy to grow the crop and convert it into ethanol and co-products = net renewable energy gain.

#### Energy budgets.

A group of engineer consultants in BC have provided a detailed analysis of the energy costs and greenhouse gas emissions of making ethanol and distillers dried grains and solubles (DDGS)(the main byproduct of grain fermentation) from corn grain in Ontario (Levelton et al., 1999). This is one of the most up to date and detailed analyses of ethanol production in Canada. They calculated that the ratio of energy output to energy input ranged from 1.50 to 1.83 depending on the end use of the ethanol. By 2010, they calculated that the energy output to input ratio could rise to 1.82 to 2.23. These energy budgets include all the energy costs to grow the corn grain, transport it to the ethanol plant and convert it into ethanol and DDGS. Credits were taken into account for the energy costs to make the animal feeds which were replaced by DDGS. The calculations also took into account the energy savings achieved in the oil refinery due to using ethanol to provide some of the octane requirements of the final gasoline-ethanol blend. Ethanol replaced octane enhancing oil-based chemicals which required more energy to produce.

More recently, a similar study has been done for ethanol produced from wheat grain in western Canada ((S&T)<sup>2</sup>, 2003). This study calculated that the ratio of energy output to input was 1.45 for ethanol produced from wheat, compared to 1.53 for ethanol produced from corn in Ontario.

These energy studies do not include the energy costs of manufacturing and repairing the farm machinery used to grow the crop nor the equipment employed in the ethanol plant. Studies done in 1990 by Giampetro and Pimentel (1990) found that these costs were significant for farm machinery. However, these are now expected to be considerably smaller, since the energy costs to produce steel and convert it into farm machinery have declined greatly in the last 20 years. One recent study calculated that the energy to produce and repair farm machinery was now 40 to 50% less than energy costs used in calculations based on data calculated some 20 years ago (Coxworth, 1998). Machinery energy costs and GHG emissions (from machinery production and repair) were now in the range of 5% of total energy and GHG emission costs for spring wheat production in western Canada. Given the controversy concerning inclusion of the energy costs and greenhouse gas emissions from farm machinery and equipment in an ethanol plant, it would be desirable to repeat the wheat to ethanol energy and greenhouse gas budget study and include the equipment energy and greenhouse gas emissions costs as well. It should be possible to modify the computer program used in those studies to include machinery energy costs.

#### Greenhouse gas budgets.

Levelton et al. (1999) calculated that a 10% ethanol blend in gasoline would reduce total greenhouse emissions, compared to straight gasoline, by 3.9 % in 2000, rising to 4.6% in 2010, as the efficiency of growing the corn grain and converting it to ethanol improves, and the energy

costs to produce low sulfur content gasoline increases. These greenhouse gas emissions were calculated on the basis of grams of carbon dioxide equivalents emitted per kilometre driven. This method of measurement takes into account the different energy contents of ethanol and gasoline (ethanol has only about 2/3's the energy content of gasoline, L/L) but the 10% ethanol blend has a slightly better energy specific fuel efficiency.

Levelton et al's study (1999) estimated that the average fuel efficiency of the vehicle fleet in Canada would increase from 9.6 L/100 km in 2000 to 9.0 L/100 km in 2010, an improvement of 6.25%. This improvement in fuel efficiency would also reduce greenhouse gas emissions. The combined effects of ethanol and improvements in fuel efficiency are shown in Table 1. It should be noted that the reductions in GHG emissions were greater from improvements in efficiency of vehicles than from addition of ethanol made from corn grain, although both effects were significant.

In the most recent study ((S&T)<sup>2</sup> Consultants, 2003), it was calculated that 100% ethanol fuel produced from Manitoba wheat would generate 50% less greenhouse gases than gasoline, ethanol from Ontario corn grain about 48% less greenhouse gases, and ethanol from Saskatchewan wheat about 43% less greenhouse gases than gasoline.

**Table 1. Effects of addition of ethanol (in a 10% blend in gasoline) and improvements in fuel efficiency of vehicles on greenhouse gas emissions. Emissions reported as g eCO<sub>2</sub>/km. Comparisons of effects in 2000 with effects in 2010. Adapted from Levelton et al., 1999.**

Year	Emissions from gasoline	Emissions from 10% ethanol/90% gasoline blend	Reduction in emissions due to ethanol (%)
2000	317.1	304.9	3.9
2010	298.3	284.5	4.6
Reduction in emissions due to fuel efficiency gains (%)	5.9	6.7	10.3 (combined effects of ethanol and fuel efficiency)

#### **2.4.2. Ethanol produced by fermentation routes from lignocellulosic raw materials.**

Materials such as straw, corn stover (the crop residue from corn grain production), fast growing trees such as hybrid poplar or grass hays such as switchgrass are more difficult to convert into ethanol than is grain. These lignocellulosic materials have to be treated with high pressure steam or weak acids to render the cellulose and hemicellulose in them reactive to enzymes which will hydrolyze the cellulose to simple sugars ready for fermentation. Strong acids can also be used to hydrolyze the materials into simple sugars. Some of the hemicellulose may be hydrolyzed into simple sugars by the action of weak acids. The hemicellulose fraction consists of a variety of sugars, not all of which are fermentable to ethanol by conventional yeasts. Thus different microorganisms have been genetically altered to be capable of fermenting all the sugars produced from the hemicellulose fraction. These transgenic organisms will be contained in a factory, which should make them more easily controlled than a transgenic crop.

The byproduct from hydrolysis of lignocellulosic raw materials is lignin, the material which glues wood and straw together and makes them rigid. This material is separated from the sugars produced. It is then burned to produce the process steam and electricity required by the process. Excess electricity may be produced for sale off the site. Thus the fossil fuel energy costs of this process are low, since renewable energy from lignin is used instead.

The processes to make ethanol from lignocellulosic raw materials is still not commercial. Therefore estimates of net energy and greenhouse gases are only reported for the year 2010.

#### Energy budgets.

Levelton and (S&T)<sup>2</sup> calculated that ethanol produced from switchgrass in Ontario would yield 25 times as much ethanol fuel energy as the fossil fuel energy required to produce it. Corn stover in Ontario would produce 18 times the ethanol energy as the fossil fuel inputs required. These very high renewable energy ratios reflect the fact that most of the energy required to produce the ethanol is derived from combustion of the lignin produced as a byproduct of the fermentation process.

#### Greenhouse gas emission budgets.

Levelton and (S&T)<sup>2</sup> calculated that a 10% blend of ethanol in gasoline in 2010 would reduce greenhouse gas emissions by 6.9% if the ethanol was produced from switchgrass and 6.2% if the ethanol was produced from corn stover. The reduction in greenhouse gases is not as large as the reduction in fossil fuel energy compared to energy output due to factors such as nitrous oxide emissions from soils, carbon sequestration in soils, co-product credits for electricity, etc., which do not affect the energy output:input ratio, but do affect the net greenhouse gas emissions. Michael Wang of the Argonne National Laboratory in the USA obtained similar results based on American processes (Wang, 1998).

### **2.4.3. Ethanol produced by gasification of biomass.**

This method of production is still in too early a stage of development to calculate energy and greenhouse gas budgets. Most of the energy requirements are met from biomass sources, so that it is anticipated that fossil fuel energy cost would be low, and greenhouse gas emissions low also.

## **2.5. Controversies around fuel ethanol.**

### **2.5.1. Renewable fuel alternatives to ethanol.**

#### Hydrogen as the ultimate fuel for vehicles.

Before discussing the controversies around ethanol, it may be useful to examine progress towards a hydrogen fuel, which many now regard as the ultimate goal as a fuel for the world's transportation sector (e.g., Dunn, 2001). The U.S. Department of Energy has recently announced that hydrogen will be the vehicle fuel of the future and has initiated a new R&D program with this goal as the objective (Chemical and Engineering News, 2002). Hydrogen would be used as a fuel in fuel cells. The fuel cells would generate electricity from the hydrogen and use the electricity to drive electrical motors, which would in turn drive the vehicle.

Recent discoveries:

It has long been a dream to use the sun's energy directly to split water molecules to release hydrogen gas:  $\text{Water} + \text{sunlight} + \text{catalyst} \rightarrow \text{hydrogen} + \text{oxygen}$ . This process is called the photochemical splitting of water. Recently it was discovered that adding carbon to the well-known water-splitting catalyst titanium dioxide (a cheap chemical used to make white paint) increased the material's ability to absorb visible light. The change boosted the ability of titanium dioxide to convert the energy in sunlight to hydrogen more than eightfold, to 8.5% (Khan et al., 2002). This efficiency is just below the US Department of Energy's goal of 10% for a commercially viable catalyst. Khan believes it may be possible to pack more carbon into the titanium dioxide to further improve its ability to absorb solar energy and split water into hydrogen and oxygen (Service, 2002a).

The second major problem with using hydrogen as a fuel for vehicles is the fact that it is a light weight gas which needs to be compressed for storing as a fuel source in a vehicle. This makes it very difficult to store enough of it in a tank to drive the vehicle very far. Recently it was discovered in Korea that two common conducting plastics (plastics that conduct electricity) could hold up to 6% of their weight in hydrogen at room temperature (Cho, reported by Service, 2002b). When these two plastics, polypyrrole and polyaniline, were treated with hydrochloric acid, the storage capacity for hydrogen jumped to 8%. This slightly exceeds the goal of 6.5% needed for a viable hydrogen-storage material. It still remains to be determined whether the plastics will give up the hydrogen when needed. This is being investigated now.

These are two very recent discoveries and it is not clear whether they will be some of the breakthroughs needed to enable hydrogen to be produced from renewable sources cheaply and whether the hydrogen will be stored cheaply enough to be carried in a vehicle as a fuel source.

In the meantime, hydrogen can be obtained by reforming natural gas. This process was assumed to be the route to obtain hydrogen for use in fuel cell-powered vehicles in Torrie et al.'s study of a low-greenhouse gas future for Canada's transportation sector (Torrie et al., 2002). The very high efficiency of fuel cells compensated for the use of a fossil fuel to produce hydrogen. Renewable sources of hydrogen, such as the photolysis of water route described previously, could be introduced as that technology became commercially competitive.

Hydrogen can also be produced by gasification of biomass, although this route is more expensive than making hydrogen from reforming of natural gas.

Ethanol and gasoline can be catalytically converted into hydrogen by use of a partial oxidation reformer mounted in the vehicle. The hydrogen would then pass into a fuel cell for conversion into electricity. The need for a reformer would increase the cost and complexity of the vehicle drive system.

Thermal depolymerization oil from organic wastes and byproducts.

Thermal depolymerization of organic materials has been shown to produce an oil similar to a mixture of heating oil and gasoline (Lemley, 2003). This product, after further refining, could become an alternative to ethanol as a renewable fuel for vehicles. It will be discussed in section 4

of this report.

### **2.5.2. Issues concerning ethanol produced from grain.**

Most of the controversy about fuel ethanol concerns ethanol produced from grains such as corn in Ontario and Quebec and wheat in western Canada.

#### 2.5.2.1. Ethanol is more expensive than gasoline and needs economic incentives to compete.

Most renewable fuels and energy sources have needed some incentives in their early stages of production.

In the case of ethanol produced from grain, the two strategies being examined to reduce ethanol costs are 1) development of methods to reduce the costs of fermentation and 2) development of methods to produce more valuable coproducts to help offset the cost of ethanol production.

Very high gravity fermentation is a technology to ferment higher concentrations of starch than is normally done, so as to obtain higher final concentrations of ethanol in the fermented material mixture (called beer). Concentrations of ethanol over 22% have been obtained in laboratory experiments (Ingledew, 2002) and the US industry is apparently adopting this technology. More ethanol is obtained per unit volume of fermentation equipment and less energy is required to distill the ethanol from the beer, thus saving energy.

The second approach is to turn the ethanol plant into a biorefinery which obtains a variety of food and feed products from grain, as well as producing ethanol. Various commercial ethanol plants have tried integration of ethanol production with food production with various degrees of success. Madson described how the Reeves Agri-Energy facility in Garden City, Kansas, integrated a number of food production aspects into an ethanol plant (Madson, 1990). Reeves purchased poor quality grain and grain screenings as the material for fermentation. The thin stillage and wet distillers grains were fed in the wet condition to cattle in an adjacent feedlot. No drying was needed of the fermentation by-products, this saving all the drying energy costs. The warm water from the ethanol plant was used to raise tilapia fish. The manure from the feedlot was used as fertilizer for the production of forage and grain. The waste water from the raising of tilapia fish was used to irrigate the land for growing forages and grain crops. Natural gas was burned in a cogeneration plant to produce electricity and steam for the ethanol plant.

There are limits to how much of feed grains such as corn can be diverted to production of ethanol and DDGS. It would take half the corn grain production in the USA just to produce enough ethanol to add 10% to all the gasoline used in the USA (Ingledew, 2002). Before this limit was reached, it is likely that the price for DDGS would be depressed to the level that ethanol production was unprofitable, even with federal and state financial supports.

#### 2.5.2.2. Other uses for the subsidy dollars: example of reducing methane emissions from manure.

Holle (2002) has calculated that the subsidies to ethanol produced from grain in Manitoba could cost up to \$35 million per year. Are there better ways to spend these dollars to reduce greenhouse gas emissions? Manitoba has a large livestock industry, particularly pig production in large-scale intensive operation hog barns. It is known that animal manures are a major source of

greenhouse gas emissions, particularly methane (Janzen et al., 1998). Feedlots and hog barns are potential sites for anaerobic digestion processing to yield biogas (principally methane plus some carbon dioxide) plus a stabilized digested manure with reduced odors and more suitable for use as a fertilizer.

Example: A system for treating manure to produce methane is being tested at a Hutterite colony in Alberta (MacArthur, 2003). The BioGem Power Systems unit produces biogas, stabilized manure and recycled water from manure produced by hog barns, poultry barns and a feedlot. When there are water shortages, such as during a drought, the recycled water may be one of the main benefits from the system. Biogas is used to produce electricity which is sold to the grid as peaking power for 10 cents per kWh. The Hutterite colony expects to pay off the \$2 million capital costs in about eight years. One of the most important benefits is the great reduction in smell from all the manure formerly not treated.

Helwig et al. (2002) concluded that one of the main restraints on more treatment of manure to generate biogas was the large capital cost. Would it be possible for governments to offer support programs for capital costs for such manure treatment systems to encourage greater adoption of such technologies? Note that the only financial support for the Hutterite colony system was the willingness of the utility to purchase electricity from the colony as peaking power at 10 cents per kWh.

In the future, government support for capital costs for various methods to reduce greenhouse gas emissions may be a less expensive route to follow than continual subsidies.

#### 2.5.2.3. Greenhouse gas emissions from agriculture.

Agriculture is a surprisingly large emitter of greenhouse gases. About 8.3% of all Canadian GHG emissions in 2000 were due to agriculture (Environment Canada 2002). The principle sources of greenhouse gases from agriculture are not carbon dioxide but methane and nitrous oxide. About 18 mt (millions of tonnes) of methane (expressed as CO<sub>2</sub> equivalents) are released by the digestive processes in ruminant animals (called enteric fermentation). Some 9.4 mt of methane (as eCO<sub>2</sub>) are released from decomposition of manures under restricted oxygen conditions and 24 mt eCO<sub>2</sub> are released as nitrous oxide from soils as a result of soil microorganisms breakdown of nitrogen fertilizers, manures, legume crops and crop residues.

Not counted in this system of accounting are the GHG emissions from fuels, fertilizers, pesticides and machinery manufacture and use. If these are included, agriculture GHG emissions would be increased a further 4-5% (see Janzen et al., 1998). For example, direct and indirect emissions of CO<sub>2</sub> from fuels, fertilizers, pesticides, machinery and building manufacture and repair, and electricity employed on farms in 1996 was estimated at 26 mt CO<sub>2</sub> (Janzen et al., 1998, p. 24, table 7).

#### 2.5.2.4. Is making ethanol from grain energy efficient?

Substantial improvements in energy efficiency in crop production and in ethanol production have occurred in the last 20 - 25 years or so. Thus Swanton et al. (1996) calculated that the energy costs to produce corn grain dropped from 3.36 GJ/t (gigajoules per tonne) in 1975 to 1.69 GJ/t in 1991. The largest effects were related to methods of manufacture and amounts of nitrogen

fertilizer used for crop production. Less energy is now required to make nitrogen fertilizer ( a drop of 11%/t of nitrogen supplied). The rate of nitrogen fertilizer applied decreased from 150 kg N/ha in 1975 to 100 kg N/ha in 1991. Part of this drop was related to increased use of green manure legume cover crops in the wheat crop preceding corn in the rotation.

Potential to reduce the energy costs of ethanol production also exists. Already mentioned is the employment of very high gravity fermentation to reduce energy and economic costs (see section 3.1). The most energy efficient plant in the USA was 31% more energy efficient than the least. Considerable room exists to improve energy efficiency. Levelton et al. (1999) calculated that the ratio of energy output to input was 1.50 : 1 at the present time for ethanol produced from corn grain in Ontario. This was estimated to increase to 1.82 : 1 by 2010.

An important part of these energy efficiency gains comes from using ethanol as part of the oil refinery's strategy for gasoline production. This reduces the energy cost of gasoline manufacture (Levelton et al., 1999). Ethanol not only replaces gasoline volume, but it also adds octane to the gasoline pool. This results in an energy savings in the refinery, which essentially provides an energy credit for ethanol.

This system was pioneered by the Sunoco refinery in Ontario. The ethanol is blended at the major terminals to avoid problems with pipeline distribution of ethanol-gasoline blends.

#### 2.5.2.5. Does ethanol production from grain compete with using grain for feed or food?

There seems to be near consensus that ethanol produced from grain will not replace even 10% of all the gasoline used in Canada today. It would require 3.8 billion litres of ethanol to replace 10% of the 38 billion litres of gasoline consumed in 2000. However, ethanol produced from other sources, such as lignocellulosic materials or black liquor solids (see section 2.3.2 and 2.3.3) could expand ethanol production considerably. Furthermore, ethanol is not the only product produced from grain fermentation, and considerable amounts of feed and food materials can, and are, produced also.

Corn grain production increased faster than demand for ethanol in the USA (Levelton et al., 1999). In 1978, US corn grain production was 184.6 million tonnes from 29.11 million hectares. In 1998, corn grain production was 247.9 million tonnes from 29.38 million hectares (ie. almost no increase in land requirements). Thus corn grain production increased by 63.3 millions tonnes in this time period. In 1998, ethanol production of 5.3 billion litres consumed 13.7 million tonnes of grain. Thus the demand for corn for ethanol has been met by a modest fraction (less than 1/4) of the total increase in corn production. About as much DDGS was produced as ethanol, so the actual amounts of feed materials for livestock has actually increased considerably since 1978.

Food supply for the poor in developing countries:

The argument has been made that using crops for fuel in developed countries takes food from the hungry in developing countries, since we could better export food surpluses in developed countries to feed the poor in developing countries. However, a recent study demonstrated that considerable increases in food production can be achieved in developing countries themselves, using low-cost methods of production. This could reduce the need for food imports, which poor countries could often find very expensive.



Much of the malnutrition in developing countries occurs in rural areas. A recent study from the UK shows promise on how this problem could be reduced (Pretty and Hine, 2001). The aim of this project, called SAFE-World, was to audit recent worldwide progress towards sustainable agriculture, and assess the extent to which such projects/initiatives, if spread on a much wider scale, could feed a growing world population. The study surveyed 208 projects from 52 countries (mainly developing countries).

The survey found that average food production per household increased by 73% usually using cheap, low-cost, locally-available technologies and inputs. Projects ranged in size from intensive kitchen gardens to fairly large-scale farms in Brazil and Argentina adopting zero-tillage methods of crop production. In Madagascar, a new system of rice intensification improved rice yields from some 2 t/ha to 5, 10 or even 15 t/ha without use of purchased pesticides or fertilizers. Elements of the new rice system are being adopted by other countries, including China.

The conclusion is that development and adoption of sustainable agricultural techniques, using systems that poor people can afford, can substantially increase food production in developing countries. In most of the cases studied, food production was increased on existing farmland, thus avoiding cutting down rainforest (for example) to grow more food.

#### 2.5.2.6. Air pollution effects of ethanol.

Ethanol blended gasoline can reduce exhaust emissions of carbon monoxide and hydrocarbons. Emissions of nitrogen oxides (NO and NO<sub>2</sub>) are dependent on the fuel characteristics and how the ethanol is blended (Levelton et al., 1999). If ethanol is used to replace other high octane components such as olefins and aromatics, nitrogen oxides can be reduced. Nitrogen oxides can increase if ethanol is splash blended, but that is not done in Canada. In splash blending, as is frequently done in the USA, the composition of the gasoline is not changed when it is blended with ethanol. In Canada, the most volatile components of ordinary gasoline are not included in the gasoline used for blending with ethanol.

In newer vehicles (post 1994 model year) or so-called low emission vehicles (LEV), oxygenates such as ethanol cause only a small reduction in carbon monoxide emissions. Thus this reason (reductions in carbon monoxide emissions) for addition of ethanol will be reduced over time and we will be left with the reduction in greenhouse gas emissions as the main reason for use of ethanol.

Acetaldehyde is produced by the burning of ethanol in an engine. According to the Royal Society of Canada, the emissions are not considered to be a serious air pollution concern, since they are effectively removed by the vehicle's catalytic converter (Royal Society, quoted by the Canadian Renewable Fuels Association, 1999).

Ethanol production plants have been found to release acetaldehyde, formaldehyde and acrolein (C&EN, 2002). The industry has stated that these emissions will be controlled in the future.

Fermentation routes to ethanol, whether from grain or from lignocellulose raw materials, involves large amounts of water. Waste water from these processes will need to be treated before

discharge. This adds to the costs of ethanol produced by such routes. Gasification routes to ethanol, methanol or hydrogen do not involve such large amounts of water.

Ethanol fueled light duty vehicles (cars and light trucks) were found to release about the same amount of nitrous oxide as gasoline powered vehicles, but about 50% more methane, although the amounts of methane were very small (Lipman and DeLucchi, 2002). It remains to be seen how significant a problem this is.

Significant amounts of oxygenated hydrocarbons, mainly methanol and acetone, but also small amounts of ethanol and acetaldehyde, have been measured in the troposphere (Singh et al., 1995). It is unclear from the initial results whether the ethanol and acetaldehyde resulted from use of ethanol fuels or were the result of natural processes, including biomass burning. These oxygenated molecules could interact with hydroxy radical in the atmosphere. The possible effect of increased ethanol production in the future on the presence of ethanol in the troposphere will need to be watched.

## **2.6. Greenhouse emissions reduction potential of fuel ethanol.**

Stumborg (2002) estimated that 2.8 billion litres of ethanol could be produced from agricultural sources in Canada; about 1.7 billion litres could be produced from grain and the remainder (1.1 billion litres) from cereal straw and corn stover. This would enable about 74% of all present consumption of gasoline to be blended with 10% ethanol, which is approximately double the figure in the Canadian GHG plan. Only 15% of total grain production was assumed to be available for ethanol and DDGS production, to avoid conflicts with conventional food and feed markets. Crop residues would only be used surplus to soil protection and animal feed needs. The total greenhouse gas reduction (compared to gasoline) would be 4.2 million tonnes of carbon dioxide equivalents. For comparison, gasoline consumption in 2000 in Canada was 38.3 billion litres. Total GHG emissions from gasoline consumption were about 96 million tonnes of carbon dioxide equivalents in 2000 (Environment Canada, 2002).

In the future it may also be possible to produce ethanol from gasification of black liquor and forest residues. Potential production from these sources has been estimated to be in the range of 5.8 to 7.3 billion litres, but much further research needs to be done on the gasification route.

As Torrie et al. (2002) have pointed out, a larger, but compatible, reduction in greenhouse gases from the transportation sector of the economy can be achieved by adoption of more fuel efficient vehicles.

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### 3. BIODIESEL

Biodiesel is the technical term for any methyl or ethyl ester of fatty acids used for fuel in diesel engines, as a lubricant or for other industrial applications. It is usually made by reacting vegetable oils, such as canola or soybean oil, with methyl alcohol in the presence of a catalyst such as sodium hydroxide. The product can also be made from animal fats or greases and recycled cooking oil. The reaction converts the triglyceride structure of the oil or fat into the much lower viscosity and lower molecular weight methyl esters and leaves a byproduct of glycerine.

A detailed analyses of the potential of biodiesel for application in the diesel fuel sector of the Canadian transportation sector has been done for Natural Resources Canada (Levelton and (S&T)<sup>2</sup>, 2002). This analysis included energy budgets, greenhouse gas budgets and economics of production of biodiesel from canola oil, soybean oil, waste animal fats and recycled cooking oils.

As described in the introduction to this report, biodiesel is a major renewable fuel in western Europe, where about 1.3 million tonnes are used annually, mostly in low-level blends (less than 20%) in regular diesel fuel. Small amounts are produced in the USA, generally for special situations such as urban buses, where the ability of biodiesel to lower air pollutants levels is particularly desirable.

#### 3.1. Air pollution reduction potential of biodiesel.

According to the EPA in the USA, biodiesel can lower a number of air pollutants when used as a 20% blend with diesel fuel (Table 2).

**Table 2. Reductions of air pollutants due to addition of 20% biodiesel to diesel fuel.**

Air pollutant	Reduction compared to 100% diesel fuel (%)
Carbon monoxide	10
Particulate matter	15
Total hydrocarbons	10
Sulfate emissions	20
Nitrogen oxides	- 2 (increase)
Methane	No change

Particulates have been implicated as potential carcinogens and as a major factor in deaths associated with air pollution. More recently, black carbon (soot) has been suggested as a serious factor in global warming (Menon et al., 2002; Chamiedes and Bergin, 2002; Jacobson, 2002). Thus methods, such as the use of biodiesel, which reduce black carbon emissions from diesel engines would have a double benefit: reduction in air pollution and reduction in global warming potential.

### Comparison of biodiesel with adoption of diesel-electric hybrid engine systems to reduce air pollution.

Even larger reductions in air pollution have been measured by replacement of diesel engine powered buses with diesel-electric hybrid buses. Bus trials in Brazil with diesel-electric buses measured a 90% drop in particulate matter, a decrease in carbon monoxide of 60-70%, and a reduction in nitrogen oxides of 25-30% (Clean Fuels and Electric Vehicles Report, 2002a). Trials in Oregon with diesel-electric hybrid buses recorded a 60% improvement in fuel efficiency (Clean Fuels and Electric Vehicles Report, 2002b). Combinations of low-sulfur diesel fuel with adoption of diesel-electric hybrid technology enabled the use of particulate traps to greatly reduce particulate matter emissions (Clean Fuels and Electric Vehicles Report, 2000). Diesel-electric hybrid engine powered buses are considerably more expensive than regular diesel buses, however (Clean Fuels and Electric Vehicles Report, 2002c).

In theory, diesel-electric hybrid vehicles could employ biodiesel/diesel fuel blends instead of conventional diesel fuel, with the potential for additive benefits in reductions in air pollutants and GHG emissions.

## **3.2. Greenhouse gas emission reductions by use of biodiesel.**

### 3.2.1. Biodiesel used as a fuel replacement in blends with diesel fuel.

Levelton and (S&T)<sup>2</sup> (2002) calculated the greenhouse gas emissions from various sources of biodiesel and compared them to conventional diesel fuel (Table 3).

**Table 3. Total greenhouse gas emissions from biodiesel and conventional diesel fuel.**

Fuel source	GHG emissions in kg eCO <sub>2</sub> /L
Diesel fuel	3.12
Canola biodiesel	1.25
Soybean biodiesel	1.27
Animal fat biodiesel	0.29
Recycled cooking oil biodiesel	0.71

The GHG calculations include all steps in the process including growing the crop, separating oil from the seed, conversion of the oil into biodiesel. All GHGs were included and credits were given for all the coproducts produced. Co-products include oilseed meal and glycerine.

The federal greenhouse gas reduction plan assumed that 500 million litres of biodiesel would be produced in 2012, with a total GHG emissions savings of 1.1 mt of eCO<sub>2</sub> per year. To put this amount of biodiesel in perspective, diesel fuel consumption in 2000 was 23.2 billion litres, which had risen from 16.7 billion litres in 1990, a larger increase than the increase in gasoline consumption in the same period. Our assumption is that this calculation of GHG reductions by employment of biodiesel is based on the fuel savings benefits of biodiesel and does not include any fuel efficiency gains, as will be discussed next.

### 3.2.2. Biodiesel used as a lubricity improvement agent.

Addition of small amounts of canola biodiesel to Canadian diesel fuel was found to improve fuel efficiency and reduce engine wear (Hertz, 2001). Most of the trials were performed with a TDI diesel VW New Beetle. Canola biodiesel was added at the 0.5% level to commercial diesel fuel purchased at the pump. Over seven trials from the fall of 1998 to the winter of 2000, the average improvement in fuel efficiency was 5.8% and a reduction in engine wear of 51.4% was measured.

No trials at these low levels have been conducted with large trucks to date, as far as we are aware. The potential effects in large trucks and the potential for all diesel fuel used in Canada were calculated by Hertz et al. (2001):

- Addition of 0.5% canola biodiesel and a fuel efficiency improvement of 4% was assumed.
- Every litre of biodiesel added resulted in a GHG emissions reduction of 27 kg eCO<sub>2</sub> due to the fuel efficiency gains for the whole fuel (99.5% diesel and 0.5% biodiesel).
- If these efficiency gains were applied to all diesel fuel used in 1999 in Canada (22.17 billion L), the total GHG reduction would be 2.86 million tonnes of CO<sub>2</sub>,
- The profit from these GHG reductions would be \$279/t of CO<sub>2</sub>.

Large truck trials are needed to confirm or not whether fuel savings of this magnitude (4%) can be achieved. The amounts of vegetable oil production needed to add 0.5% biodiesel to all Canadian diesel fuel was calculated to be about 94 million kg of oil. This could be obtained from 2.6% of canola seed production in 1999.

### **3.3. Costs of biodiesel.**

Levelton and (S&T)<sup>2</sup>(2002) calculated the following costs of biodiesel, based on prices of vegetable oils and animal fats in 2002: Canola or soybean oil biodiesel = 63 cents/litre, animal fat biodiesel = 36 cents/litre. Diesel fuel rack prices are roughly in the range of 20 to 30 cents per litre, depending on fluctuations in crude oil prices. Biodiesel has about 91% the energy value of diesel fuel. This puts biodiesel at a further price disadvantage compared to diesel fuel, if the only effect of biodiesel use is fuel substitution, and no efficiency gains are achieved.

Large reductions in federal and provincial taxes would be needed to encourage oil companies to add biodiesel at levels above 2% to diesel fuel, if only fuel substitution effects were obtained. If fuel efficiency gains and engine wear reduction benefits can be demonstrated at levels of 1% or less in large truck trials, then addition of small amounts of biodiesel, primarily as a lubricity improvement agent, might be economically interesting. Low sulfur diesel fuel is to be required in Canada after 2005. It is expected to have lower lubricity than the current diesel fuel used in Canada. Thus the addition of lubricity improvement agents, such as biodiesel, could become more attractive after 2005 in Canada. Various studies have indicated that Canadian diesel fuel has poor lubricity values, compared to diesel fuel used in most other countries. This emphasizes the importance of improving fuel lubricity in Canadian diesel fuel, such as by addition of biodiesel.



### **3.4. Amounts of biodiesel potentially available in Canada.**

A rough estimate is that about 1.5 million tonnes of oils and greases might become available for biodiesel production in Canada, including about 100,000 t of recycled cooking oils and 500,000 t of animal fats and greases. Yields of biodiesel from fats and oils are close to 100%, so about 1.5 million tonnes of biodiesel could be achieved in Canada. This translates into some 1.7 billion litres of biodiesel. The federal plan is considering about 500 million L of biodiesel in 2012, whereas Torrie et al. (2002) assumed some 420 million L of biodiesel by 2012. Neither the federal plan nor Torrie et al. (2002) considered the potential of fuel efficiency gains by using biodiesel as a lubricity improvement agent in Canadian diesel fuel. Large truck trials are needed to quantify the fuel efficiency benefits of adding small amounts of biodiesel to Canadian diesel fuel.

If these truck trials confirm the estimated GHG emissions reductions, then addition of biodiesel to all diesel fuel in Canada could result in larger reductions than the Canadian plans suggests.

### **3.5. Use of bioproducts to improve Canadian diesel fuel.**

Martin Reaney (2002) has suggested that the biodiesel industry should work with the oil industry to determine how small amounts of biodiesel, and other products made from biomass resources, could best be integrated with other additives to improve the performance and fuel efficiency of diesel fuel. Canadian diesel fuel has been found to have low lubricity values compared to diesel fuel from other countries (Hertz, 2001; Reaney, 2002). Thus agents to improve lubricity could have an important role to play with Canadian diesel fuel. Other products made from biomass raw materials might also be added to improve other performance factors, such as the cetane number, a measure of diesel fuel value.

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## 4. THERMAL DEPOLYMERIZATION OILS

A new process for treating organic waste materials to produce a crude oil similar to a mix of fuel oil and gasoline has been developed in the USA by Changing World Technologies (CWT)(Lemley, 2003; CWT web site: [www.changingworldtech.com](http://www.changingworldtech.com)). A recent popular description of the process (Lemley, 2003) brought this technology to my attention. Thus comments about this process should be regarded as tentative, until more information becomes available. The review article indicates that there are a number of advantages to this process that warrant further investigation.

### 4.1. CWT technology.

Lemley has summarized the process as follows:

“The thermal depolymerization process can convert a wide range of waste materials into oil and other useful by-products, in proportions that vary according to the specific type of feedstock run through the works.”

“Feedstock is funneled into a grinder and mixed with water to create a slurry that is pumped into a first-stage reactor, where heat and pressure partially break apart long molecular chains. The resulting organic soup flows into a flash vessel where pressure drops dramatically, liberating some of the water, which returns back upstream to preheat the flow into the first-stage reactor. In the second-stage reactor, the remaining organic material is subjected to intense heat, continuing the breakup of molecular chains. The resulting hot vapor then goes into vertical distillation tanks, which separates it into gases, light oils, heavy oils, water, and solid carbon. The gases are burned on-site to make heat for the process, and the water, which is pathogen free, goes to a municipal waste plant. The oils and carbon are deposited in storage tanks, ready for sale.”

The focus of CWT appears to have been initially on treatment of organic wastes, rather than biofuel production. The first commercial plant has been built in Carthage, Missouri, where it will process turkey offal from a ConAgra Butterball Turkey plant. The CWT plant will process 200 tons (wet basis) per day of waste. It will yield 600 barrels/day of oil and 11 tons/day of mineral fertilizer.

The CWT web site and the Lemley article suggest that the first stage reactor may employ conditions which result in supercritical water. Water at high temperatures and pressures can act as a powerful reactant, which can break down complex molecules into smaller, simpler molecules. The first stage reactor uses temperatures of about 260° C and a pressure of some 600psi. The cooking time is about 15 minutes.

The pressure is rapidly dropped at the end of the first stage, which drives off about 90% of the slurry's free water. The minerals settle out at this stage and are sent to storage tanks. The mineral-free organic material is then sent to a thermal reactor where high temperature (480° C) further breaks the material down into oils, gas and carbon. Distillation columns separate the breakdown mixture into the constituent gases, oils and carbon.

The process is energy efficient. It uses about 15% of the energy in the raw material to run the process.

The oil product is similar to a mixture of fuel oil and gasoline, with the longest chain length being about C-18 . CWT believes that the oil from the process can be produced at a cost of US\$8 to US\$12/barrel. CWT estimates that there are some 600 million tons of organic materials available in the USA, including crop residues. The energy value of the oil and gas produced would have an energy content equivalent to 4 billion barrels of oil, similar to the amounts imported into the USA per year.

Demonstration plants are to be built to process manure in Alabama and crop residues in Nevada.

CWT formed a partnership with the Gas Technology Institute to build the first pilot plant.

#### **4.2. Scale of waste treatment plants with the CWT technology.**

Experiments at the pilot plant of CWT in Philadelphia, PA, revealed that the process is not scale sensitive (Lemley, 2003). Thus plants as small as one ton per day could be economically attractive, as well as plants as large as 4,000 tons per day. Many biomass resources are scattered over large areas. Thus relatively small plants could have a number of advantages, including rural development.

#### **4.3. Final comments.**

The CWT technology demonstrates that new technologies may come along at any time which could change the viability of previous processes and products, such as biodiesel and fuel ethanol. We will need to continuously scan the technology horizon to be on the look-out for new process and determine their applicability to the Canadian energy situation. It is still too early to determine the role that the thermal depolymerization process will play in the development of renewable liquid fuels from biomass, but this process does appear to have a number of advantages for future applications.

#### **4.4. References for thermal depolymerization oil.**

Changing World Technology (CWT). 2003. Web site address; [www.changingworldtech.com](http://www.changingworldtech.com). Headquarters; 460 Hempstead Avenue, West Hempstead, NY 11552. Phone: (516) 486-0100.

Lemley, B. 2003. Anything into Oil. Discover magazine, May issue, pp. 50-57, 86.